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$\Delta Y/\Delta Z$ from fine structure in the Main Sequence based on Hipparcos parallaxes ⋆

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ABSTRACT
The slope $\Delta Y/\Delta Z$ is a quantity of interest in relation to stellar evolution, the initial mass function and the determination of the primordial helium abundance. In this paper we estimate $\Delta Y/\Delta Z$ from fine structure in the Main Sequence of nearby stars from Hipparcos data for stars with $Z \leq Z_\odot$ and find a value of about 3, which is consistent with what has been found in extragalactic H II regions and with stellar models for suitable upper limits to the initial masses of supernovae according to the IMF slope adopted.

Key words: galaxies: abundances, ISM: abundances, stars: abundances, stars: evolution

1 INTRODUCTION

The ratio $\Delta Y/\Delta Z$ of fresh helium supplied to the interstellar medium by stars relative to their supply of heavy elements is a quantity of considerable interest from several points of view. It is a test of theoretical stellar yields (combined with the initial mass function) and it governs the slope of the regression of helium against oxygen in extragalactic H II regions and hence affects the use of that regression to determine the primordial helium abundance (Peimbert & Torres-Peimbert 1976). From extragalactic H II regions, Lequeux et al. (1979) found a value of 3, combined with a primordial helium abundance $Y_{\rm P} = 0.23$, and Pagel et al. (1992) found a raw value of 6 with a similar $Y_{\rm P}$; Pagel et al. applied various corrections to their raw value of $\Delta Y/\Delta Z$ which reduced it to 4 ± 1. More recently, Izotov, Thuan & Lipovetsky (1997) have determined a higher value of $Y_{\rm P} = 0.24$, which is in better accord with Big-Bang nucleosynthesis theory with a low primordial value of $\mathrm{D/H} = 3.2 \times 10^{-5}$ (Tytler 1997), and a lower value of the slope, $\Delta Y/\Delta Z \simeq 2$, which is also closer to theoretical estimates if stars with initial masses up to $50 M_\odot$ or more undergo supernova explosions as opposed to collapsing into black holes (Maeder 1992). Various determinations of $\Delta Y/\Delta Z$ from H II regions and planetary nebulae have been reviewed by Peimbert (1995), who concludes that the data are consistent with the theoretical value of about 2.5, for the full range of the Scalo (1986) or Kroupa, Tout & Gilmore (1993) IMFs.

An independent approach to the $\Delta Y/\Delta Z$ question is the investigation of fine structure in the stellar zero-age Main Sequence, i.e. the dependence on Z of the Main Sequence location. Since concomitant changes in Y and Z push the sequence in opposite directions, for a given range of metallicities the related Main Sequences are more spread apart if the corresponding variation in Y is lower, or conversely the broadening of the Main Sequence is a decreasing function of $\Delta Y/\Delta Z$ (Faulkner 1967; Perrin et al. 1977; Pagel 1995; Cayrel de Strobel & Crifo 1995; Fernandes, Lebreton & Baglin 1996). Perrin et al., using ground-based parallaxes, could find no Z-dependence of the Main Sequence location in the luminosity–effective temperature plane for relatively metal-rich stars and deduced a large but very uncertain value: $\Delta Y/\Delta Z \simeq 5 \pm 3$. Fernandes et al., using Geneva colours and ground-based parallaxes, but without individual metallicity data, studied the scatter in the $M_V,\ B_2 - V_1$ plane and just obtained a lower limit $\Delta Y/\Delta Z > 2$ corresponding to the case in which all the scatter is assumed to be real. Cayrel de Strobel & Crifo (1995) quote preliminary absolute helium abundances for three well studied visual binary stars with Z-values ranging from 0.2 to 1.7 times solar which are all consistent with a value of $\Delta Y/\Delta Z$ between 2 and 3. In this paper we use HIPPARCOS parallaxes (ESA 1997) and infra-red flux temperatures (Alonso et al. 1996) for a sample of mainly metal-poor stars with a view to improving on the previous results. Some preliminary results of this investigation, based on fewer stars, are reported by Høg et al. (1997).

⋆ Based on data from the ESA Hipparcos astrometry satellite

2 THEORY

As has been discussed previously by Perrin et al. (1977) and Fernandes et al. (1996), the effect of metallicity on the location of the stellar Main Sequence can be seen from quasi-homology relations of the form (Cox & Giuli 1968; Fernandes et al. 1996)

$$\frac{L}{f(T_{\rm eff})} \propto \epsilon_0^{0.32} \kappa_0^{0.35} \mu^{-1.33}, \tag{1}$$

where the energy generation constant $\epsilon_0 \propto X^2$, the opacity constant $\kappa_0 \propto (1+X)(Z+Z_0)$ with $Z_0 \simeq 0.01$ (but see Section 5 below) and the molecular weight $\mu \propto (3+5X-Z)^{-1}$ leading to a magnitude offset above the zero-age, zero-metallicity Main Sequence where $X = X_0 \simeq 0.76$

$$\begin{aligned} -\Delta M_{\rm bol} \quad \simeq \quad & 1.6 \log \left[1 - \frac{Z}{X_0}\left(1 + \frac{\Delta Y}{\Delta Z}\right)\right] \\ & +0.87 \log \left[1 - \frac{Z}{1+X_0}\left(1 + \frac{\Delta Y}{\Delta Z}\right)\right] \\ & +0.87 \log \left(1 + \frac{Z}{Z_0}\right) \\ & +3.33 \log \left[1 - \frac{5Z}{3+5X_0}\left(1.2 + \frac{\Delta Y}{\Delta Z}\right)\right]. \end{aligned} \tag{2}$$

For high metallicities, around $0.7 Z_\odot \leq Z \leq 1.5 Z_\odot$, the effects of Y and Z cancel out for $\Delta Y/\Delta Z \simeq 5.5$ (Fernandes et al. 1996), but this is not the case for lower metallicities (e.g. Faulkner 1967; Cayrel 1968). In the case of an old stellar population, direct application of Eq. (2) is also not very useful in practice (as well as not being very accurate) because the effects of stellar evolution increase sharply with luminosity above, say, $M_V \simeq 5.5$, so that the sequences cannot be expected to run straight and parallel over a wide range of luminosities. It is more useful to translate Eq. (2) into a range of log $T_{\rm eff}$ at a fixed absolute magnitude using the slope of the evolved Main Sequence, which is about 20 magnitudes per dex in $T_{\rm eff}$. We thus derive

$$\begin{aligned} -\Delta \log T_{\rm eff} \quad \simeq \quad & 0.08 \log \left[1 - \frac{Z}{X_0}\left(1 + \frac{\Delta Y}{\Delta Z}\right)\right] \\ & +0.0435 \log \left[1 - \frac{Z}{1+X_0}\left(1 + \frac{\Delta Y}{\Delta Z}\right)\right] \\ & +0.0435 \log \left(1 + \frac{Z}{Z_0}\right) \\ & +0.167 \log \left[1 - \frac{5Z}{3+5X_0}\left(1.2 + \frac{\Delta Y}{\Delta Z}\right)\right]. \end{aligned} \tag{3}$$

Since the terms in Z are small, apart from $(1 + Z/Z_0)$, we can expand the logarithms, also making use of $X_0 \simeq 0.76$, to give

$$\begin{aligned} \Delta \log T_{\rm eff} \quad \simeq \quad & 0.01Z + 0.11Z(1 + \Delta Y/\Delta Z) \\ & -0.044 \log(1 + Z/Z_0). \end{aligned} \tag{4}$$

The quasi-homology fitting formula given by Faulkner (1967):

$$L \propto (X + 0.4)^{2.67} (Z + Z_0)^{0.455} f(T_{\rm eff}) \tag{5}$$

leads to a very similar relation

$$\Delta \log T_{\rm eff} \simeq 0.124Z(1 + \Delta Y/\Delta Z) - 0.057 \log(1 + Z/Z_0). \tag{6}$$

Besides chemical composition, the location of the Main Sequence of single stars also depends on: the treatment of convection and the size of core convective regions (for $M \geq 1.1 M_\odot$); rotation (for $M \geq 1.4 M_\odot$); and evolution, inducing stars to deviate from the Zero Age Main Sequence (for $M \geq 0.9 M_\odot$). As discussed by Fernandes et al. (1996), for magnitudes fainter than $M_V \sim 5.5$ all the above effects are negligible, and the broadening of the Main Sequence only depends on chemical composition, namely Z and $\Delta Y/\Delta Z$.

Therefore, Eqs. (4) and (6) provide a rough guide to the behaviour of numerically computed isochrones for magnitudes fainter than $M_V \simeq 5.5$ as a function of $\Delta Y/\Delta Z$; qualitatively, the spread in the Main Sequence is a decreasing function of this parameter.

3 THE DATA

For the present investigation, we have combined the sample studied by Høg et al. (1997), based on a proposal submitted to HIPPARCOS by one of us (BEJP) in 1982, with additional stars from the HIPPARCOS catalogue for which effective temperatures measured by the infra-red flux method (Blackwell et al. 1990) are available from the work of Alonso et al. (1996). We have chosen stars for which the HIPPARCOS parallaxes are accurate to better than ±9 %; among these, we have further selected the stars with absolute magnitudes fainter than $M_V = 5.5$, which are expected to be reliable indicators of $\Delta Y/\Delta Z$ (see Section 2). The resulting sub-sample of stars is listed in Table 1. Columns 3 to 5 list the apparent visual magnitudes, the absolute visual magnitudes and the corresponding errors, respectively.

Column 6 lists the effective temperatures. The infra-red flux temperatures from Alonso et al. are very accurate, judging from the agreement between different infra-red wavelength bands, and we assume them to have an accuracy of ±50 K, at least twice as good as the more heterogeneous temperatures available in other literature. This precision corresponds to an error of about $\pm 0.1^{\rm m}$ in the location of the Main Sequence, similar to the errors in M_V. For the remaining stars, we have taken effective temperatures and metallicities (shown in square brackets in Table 1) from either or both of the catalogues by Cayrel de Strobel et al. (1992) and Carney et al. (1994).

An important factor in comparing stellar data with theoretical isochrones is the relationship between the metallicity [Fe/H] and the heavy-element mass fraction Z (columns 7 and 8, respectively). In most cases we have used the formula by Salaris, Chieffi & Straniero (1993)

$$Z = Z_1(0.638 f_\alpha + 0.362), \tag{7}$$

where Z_1 is the solar Z ($Z_\odot = 0.019$) scaled according to [Fe/H] and f_α is the factor by which oxygen and α-particle elements are enhanced relative to iron, taking f_α from Pagel & Tautvaišienė (1995). Thus for [Fe/H] < -1, $Z = 2Z_1$. However, in the case of HD 134439 and 134440 we take $Z = Z_1$, following King (1997). We assume [Fe/H] values to have an accuracy of ±0.1 dex.

Binary stars, marked with “binary” in Table 1, were naturally excluded from further analysis.

Table 1. Data for the sample

HIC	HD (or others)	V	M_V	±	$T_{\rm eff}$	[Fe/H]	log Z	Notes
5031	6348	9.15	6.18	0.10	[4998]	[-0.67]	-2.31	
5336	6582	5.17	5.78	0.03	5315	-0.67	-2.31	μ Cas
10138	13445	6.12	5.93	0.01	[5067]	[-0.24]	-1.99	
11983	G 73-67	9.81	6.80	0.16	4756	-0.41	-2.13	
16404	G 246-38	9.91	6.14	0.19	5279	-2.94	-4.38	
17666	23439	7.67	5.72	0.12	[4892]	[-1.03]	-2.43	binary
18915	25239	8.51	7.17	0.04	4842	-1.64	-3.04	
19849	26965	4.43	5.91	0.01	5040	-0.17	-1.94	o^2 Eri
23080	31501	8.19	5.59	0.08	[5254]	[-0.33]	-2.06	
38541	64090	8.31	6.05	0.07	5441	-1.82	-3.22	
38625	64606	7.43	6.01	0.08	[5070]	[-0.97]	-2.40	binary
39157	65583	6.99	5.87	0.03	5242	-0.60	-2.27	
41269	G 51-10	10.10	7.02	0.17	4579	-0.04	-1.79	
57939	103095	6.44	6.63	0.02	5029	-1.35	-2.75	Gmb 1830
58949	104988	8.16	5.59	0.07	[5247]	[-0.23]	-1.98	
62607	111515	8.15	5.55	0.07	[5354]	[-0.81]	-2.37	
70681	126681	9.28	5.71	0.16	5541	-1.98	-3.39	
72998	131653	9.51	6.05	0.16	5311	-0.50	-2.18	excluded
73005	132142	7.77	5.88	0.03	5098	-0.55	-2.22	
74234	134440	9.45	7.08	0.11	4746	-1.53	-3.25	[Z]=[Fe/H]
74235	134439	9.07	6.73	0.09	4974	-1.47	-3.19	[Z]=[Fe/H]
81170	149414	9.60	6.18	0.16	4966	-1.34	-2.74	excluded
94931	BD +41 3306	8.84	6.10	0.07	5004	-0.42	-2.13	
98020	188510	8.83	5.85	0.10	5564	-1.80	-3.20	
99461	191408	5.32	6.41	0.01	[4893]	[-0.32]	-2.06	
104214	201091	5.20	7.49	0.03	4323	-0.05	-1.80	61 Cyg A
106122	204814	7.93	5.56	0.05	[5232]	[-0.28]	-2.02	
106947	G 126-19	9.51	5.74	0.18	5267	-0.20	-1.96	
109067	G 18-28	9.55	6.21	0.16	5411	-0.84	-2.38	excluded
111783	G 67-8	9.50	5.55	0.20	5273	-0.09	-1.86	
116351	G 190-34	9.05	5.66	0.13	5318	-0.01	-1.74	

4 COMPARISON WITH THEORETICAL ISOCHRONES

We have used grids of isochrones with different combinations of metallicity (Z = 0.0004, 0.001, 0.004, 0.008, 0.019) and $\Delta Y/\Delta Z$ (= 0, 2, 2.5, 3, 3.5, 4, 5, 6), computed from Padova evolutionary tracks normalized to the Sun: the helium content Y for solar metallicity isochrones and the mixing length parameter are calibrated so that the luminosity and effective temperature of the Sun are reproduced for a model star with appropriate age and metallicity ($Z_\odot = 0.019$). A shift of the isochrones by -0.009 in $\log T_{\rm eff}$ turned out to be necessary in our plot to fit solar-metallicity, faint Main Sequence stars. This shift will not affect our results, since for our purpose it is basically the spread of the isochrones that counts, rather than their absolute position. In fact, owing to many uncertainties in the physics of stellar models (description of convective regions, mixing length parameter, model atmospheres, opacities and so forth) our analysis is not intended to give absolute values for $Y(Z)$, but only to determine $\Delta Y/\Delta Z$ differentially on the basis of the relative separation of isochrones of different metallicity.

On the other hand, even differential effects might be sensitive to the mixing length parameter α, which in principle might not be fixed but could change with mass, metallicity and/or evolutionary phase. In our case, faint Main Sequence stars have very similar masses and are in the same evolutionary phase, so we are left with only a possible dependence of α on Z. Chieffi, Straniero & Salaris (1995), from inspection of HR diagrams of globular clusters, have suggested that the mixing-length parameter α might increase systematically with metallicity, pushing the Main Sequence downwards. If so, this could introduce systematic overestimations of $\Delta Y/\Delta Z$ from shifts in the sequence. However, this mixing-length effect was predicted to be small for the lower Main Sequence, while it is expected to increase quite sharply with luminosity, so that, for sufficiently faint stars, the use of isochrones with a constant mixing length parameter appears to be justified. Some checks on the possible role of magnitude-dependent effects other than $\Delta Y/\Delta Z$ are carried out in Section 5 below.

In Figures 1 to 3 we display sets of low Main Sequence isochrones for representative values of $\Delta Y/\Delta Z$, together with the stellar data. This first comparison suggests that $\Delta Y/\Delta Z = 0$ is excluded, because the spread of the isochrones is too great, whereas $\Delta Y/\Delta Z = 6$ is too large (i.e. the isochrones are too close); $\Delta Y/\Delta Z = 3$ gives a better fit. This can also be seen qualitatively from the location of HD 19445 (the 'star' symbol at $M_V \simeq 5.1$), a well-known old, very metal-poor star ([Fe/H] = -2.15, Alonso et al. 1996). Although it is brighter than the "useful" range of magnitudes and likely affected by evolution, we can compare its location in the plot with the most metal-poor 13 Gyr isochrone of our set. Both the $\Delta Y/\Delta Z = 0$ and $\Delta Y/\Delta Z = 6$

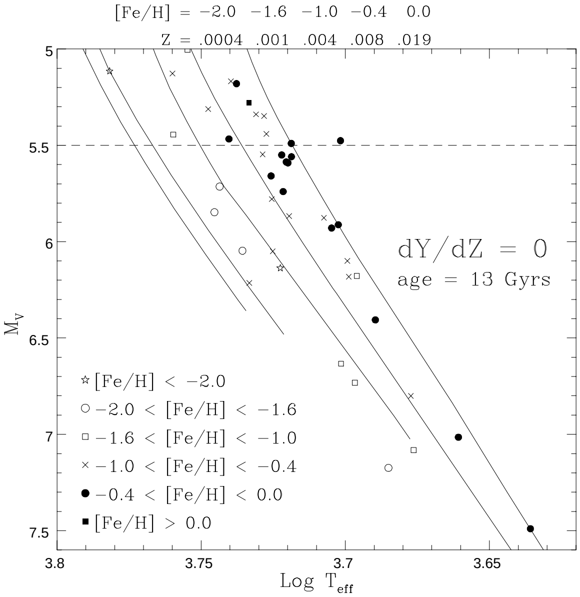

Figure 1. The stellar data from our sample are plotted against 13 Gyr Padova isochrones calculated for $\Delta Y/\Delta Z = 0$, shifted by -0.009 in $\log T_{\rm eff}$. The values of Z for the 5 isochrones, together with the corresponding [Fe/H], are indicated on top of the plot. The 'star' symbol at $M_V \simeq 5.1$ indicates HD 19445. The dashed line at $M_V = 5.5$ indicates the limiting magnitude for the "useful" data listed in Table 1. Binary stars are excluded from the plot.

case seem to be too extreme, while a good fit to this star is obtained with $\Delta Y/\Delta Z = 3$.

These impressions are, however, largely based on the extremes in the abundance range of the data, and the intermediate-metallicity stars are too scattered to allow any choice of $\Delta Y/\Delta Z$ from mere inspection. In the next section we shall try to improve on these qualitative impressions by applying a maximum-likelihood calculation based on an extension of the idea of quasi-homology.

5 STATISTICAL ANALYSIS USING QUASI-HOMOLOGY RELATIONS

A quantitative analysis of the data is possible by comparing them to theoretical relations like those discussed in Section 2. Eqs. (4) or (6) are not directly applicable, being obtained on the simplifying assumption of a totally radiative structure, while low Main Sequence stars actually have deep convective envelopes.

We have therefore established relations analogous to Eq. (6) for our numerically calculated isochrones of age 13 Gyr and in a limited range of absolute magnitude, $5.5 \leq M_V \leq 7.5$. Specifically, we have imposed that our isochrones are described by a relation of the form

$$\phi(M_V)\Delta \log T_{\rm eff} + k\log(1 + Z/Z_0) = aZ\left(1 + \frac{\Delta Y}{\Delta Z}\right), \quad (8)$$

where $\phi(M_V)$ is a normalization to allow for the convergence of the isochrones towards low luminosities. Since in our set the solar-metallicity isochrone is fixed, while the lower metallicity isochrones shift in $\log T_{\rm eff}$ according to Z and the assumed $\Delta Y/\Delta Z$, and moreover we do not know the reference $\log T_{\rm eff}(Z = 0)$, it is more convenient to re-formulate Eq. (8) as:

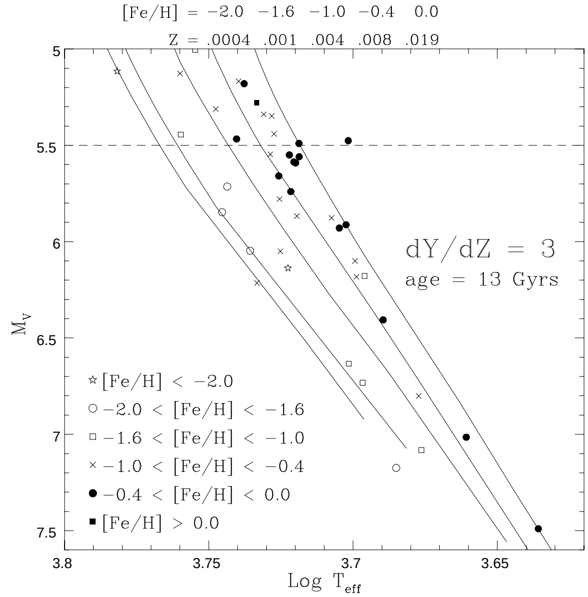

Figure 2. Same as Figure 1, but for $\Delta Y/\Delta Z = 3$.

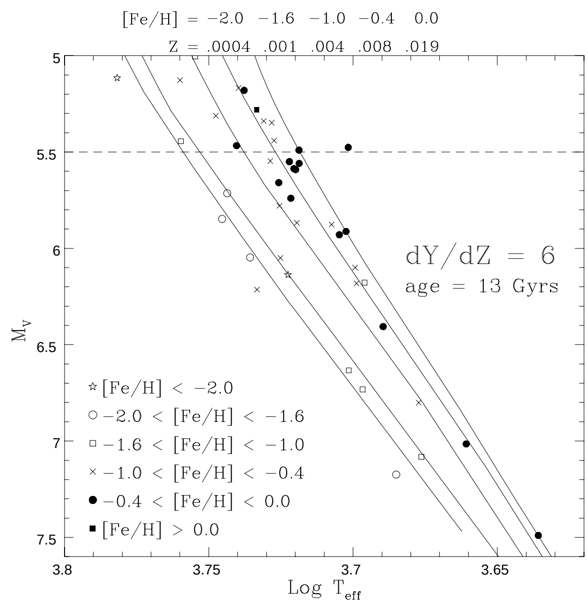

Figure 3. Same as Figure 1 and 2, but for $\Delta Y/\Delta Z = 6$.

$$\phi(M_V)\Delta' \log T_{\rm eff} + k\log\left(\frac{Z + Z_0}{Z_\odot + Z_0}\right) =$$
$$= a(Z - Z_\odot)\left(1 + \frac{\Delta Y}{\Delta Z}\right), \quad (9)$$

$\Delta' \log T_{\rm eff} = \log T_{\rm eff}(Z) - \log T_{\rm eff}(Z_\odot)$.

The scaling function $\phi(M_V)$ and the suitable values of the parameters k, a and Z_0 describing the isochrones were cali-

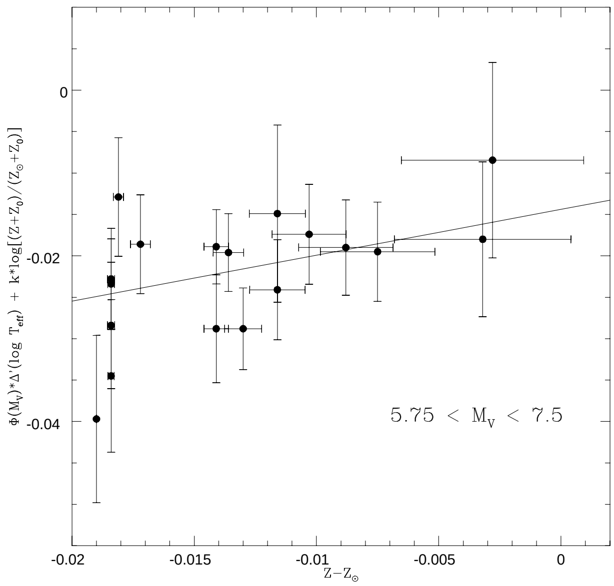

Figure 4. Maximum-likelihood regression for stars with $5.75 \leq M_V \leq 7.5$, assuming $\sigma_{T_{\rm eff}} = 50$ K and $\sigma_{\rm [Fe/H]} = 0.1$. The slope corresponds to $\Delta Y/\Delta Z = 2.8 \pm 1.8$.

brated by means of numerical experiments using *Mathematica*. The specific relation that we found is:

$$\frac{\Delta' \log T_{\rm eff}}{1 - 0.234(M_V - 6.0)} + 0.054 \log\left(\frac{Z + Z_0}{Z_\odot + Z_0}\right) = $$
$$= 0.147(Z - Z_\odot)\left(1 + \frac{\Delta Y}{\Delta Z}\right); \qquad (10)$$

$Z_0 = 0.0015$.

The coefficients are quite similar to those in Eq. (6), but Z_0 turns out to be much lower than the widely quoted value of 0.01.

We have calculated the expression on the left-hand side of Eq. (10) for the stellar data in our sample, and plotted it against $Z - Z_\odot$ with the corresponding errors on both axes. By means of a maximum-likelihood fit computed using the program of Pagel & Kazlauskas (1992), we have derived the experimental value of the slope $a(1+\Delta Y/\Delta Z)$ of the regression line, and hence $\Delta Y/\Delta Z$. Fig. 4 shows the plot for the data with $7.5 < M_V < 5.75$, together with their maximum-likelihood fit. In Table 2 we give maximum-likelihood solutions of this kind for various ranges of absolute magnitude. We considered magnitude ranges from $M_V = 7.5$ to brighter and brighter magnitudes, including one more star at each step. This procedure allows us to estimate the limiting magnitude where evolutionary effects, or possibly the mixing length effects mentioned in Section 4 which are expected to increase sharply with luminosity, begin to play a role and spoil the determination of $\Delta Y/\Delta Z$. It was further possible to isolate and exclude a few stars with large deviations from our statistical analysis (marked with "excluded" in Table 1). It turns out that all remaining stars fainter than $M_V \sim 5.75$ indicate a consistent value of $\Delta Y/\Delta Z$. For stars brighter than this, the slope of the regression line rapidly increases displaying additional effects, while for M_V fainter than 6.0, the solutions become poor owing to shortage of stars. We therefore pay most attention to the values determined in the magnitude ranges between the two horizontal lines in Table 2, and give a global estimate of $\Delta Y/\Delta Z = 3 \pm 2$ (s.e.) as the result of this investigation.

Table 2. Max Likelihood solutions for $\Delta Y/\Delta Z$; 3 stars excluded

M_V range	$\Delta Y/\Delta Z$	N(stars)
7.5 to 7.00	2.3 ± 3.0	4
7.5 to 6.80	2.3 ± 3.0	5
7.5 to 6.70	3.7 ± 2.8	6
7.5 to 6.50	3.1 ± 2.7	7
7.5 to 6.40	3.0 ± 2.5	8
7.5 to 6.15	3.1 ± 2.5	9
7.5 to 6.12	4.4 ± 2.5	10
7.5 to 6.10	4.0 ± 2.4	11
7.5 to 6.00	3.6 ± 2.2	12
7.5 to 5.92	3.5 ± 2.1	13
7.5 to 5.90	3.2 ± 1.9	14
7.5 to 5.87	3.2 ± 1.9	15
7.5 to 5.85	3.2 ± 1.9	16
7.5 to 5.80	2.8 ± 1.8	17
7.5 to 5.75	2.8 ± 1.8	18
7.5 to 5.72	3.5 ± 1.8	19
7.5 to 5.70	4.0 ± 1.7	20
7.5 to 5.60	6.1 ± 1.5	21
7.5 to 5.59	6.1 ± 1.4	22
7.5 to 5.57	6.0 ± 1.4	23
7.5 to 5.55	6.0 ± 1.4	25
7.5 to 5.50	6.2 ± 1.4	26

6 DISCUSSION

Although we have used the best available data for as many stars as possible having absolute magnitudes and effective temperatures with sufficient accuracy, our result for $\Delta Y/\Delta Z$ still has a disappointingly large uncertainty. Nevertheless we consider it an improvement on previous work, although a quite similar value ($\sim$ 3.5) was actually estimated by Faulkner (1967) thirty years ago. Our value is intermediate between those derived from extragalactic H II regions by Pagel et al. (1992) and Izotov, Thuan & Lipovetsky (1997) and also agrees well with the values quoted by Peimbert (1995), which supports the assumption that in this respect the stars in our Galaxy and in dwarf irregulars have undergone similar evolution, contrary to the suggestion that in the latter case $\Delta Y/\Delta Z$ has been increased by metal-enhanced galactic winds (e.g. Pilyugin 1993). Furthermore, we see no evidence for significant variations in $\Delta Y/\Delta Z$ relative to the precision of currently available data.

Our result is also consistent with the conclusion of Fernandes et al. (1996) that $\Delta Y/\Delta Z > 2$. Taking that lower limit together with the calculations of Maeder (1992), one finds upper mass limits for supernovae of $55 M_\odot$ for a Salpeter IMF and $100 M_\odot$ for a Scalo IMF. A similar limit has been deduced on other grounds for a Salpeter-like IMF slope by Tsujimoto et al. (1997). On the other hand, the

Miller-Scalo (1979) IMF would permit an arbitrarily high upper mass limit for $\Delta Y/\Delta Z = 2.56$ (Traat 1995).

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